An-Najah National University

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# Internal Combustion Engines 10621524

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# Introduction

- The real cycles in the internal combustion engine is very complex.
- The air (CI engine) or air/fuel mixture is ingested and mixed with the slight amount of the exhaust residual remaining from the previous cycle.
- The combustion of such mixture produces different compositions of products (e.g. $CO_x, NO_x, N_x$ …..).
- The exhaust is expelled to the surrounding, thus its an open system, a difficult system to analyse.
- To make the analysis of the engine cycles much easier, the air-standard cycles are used.

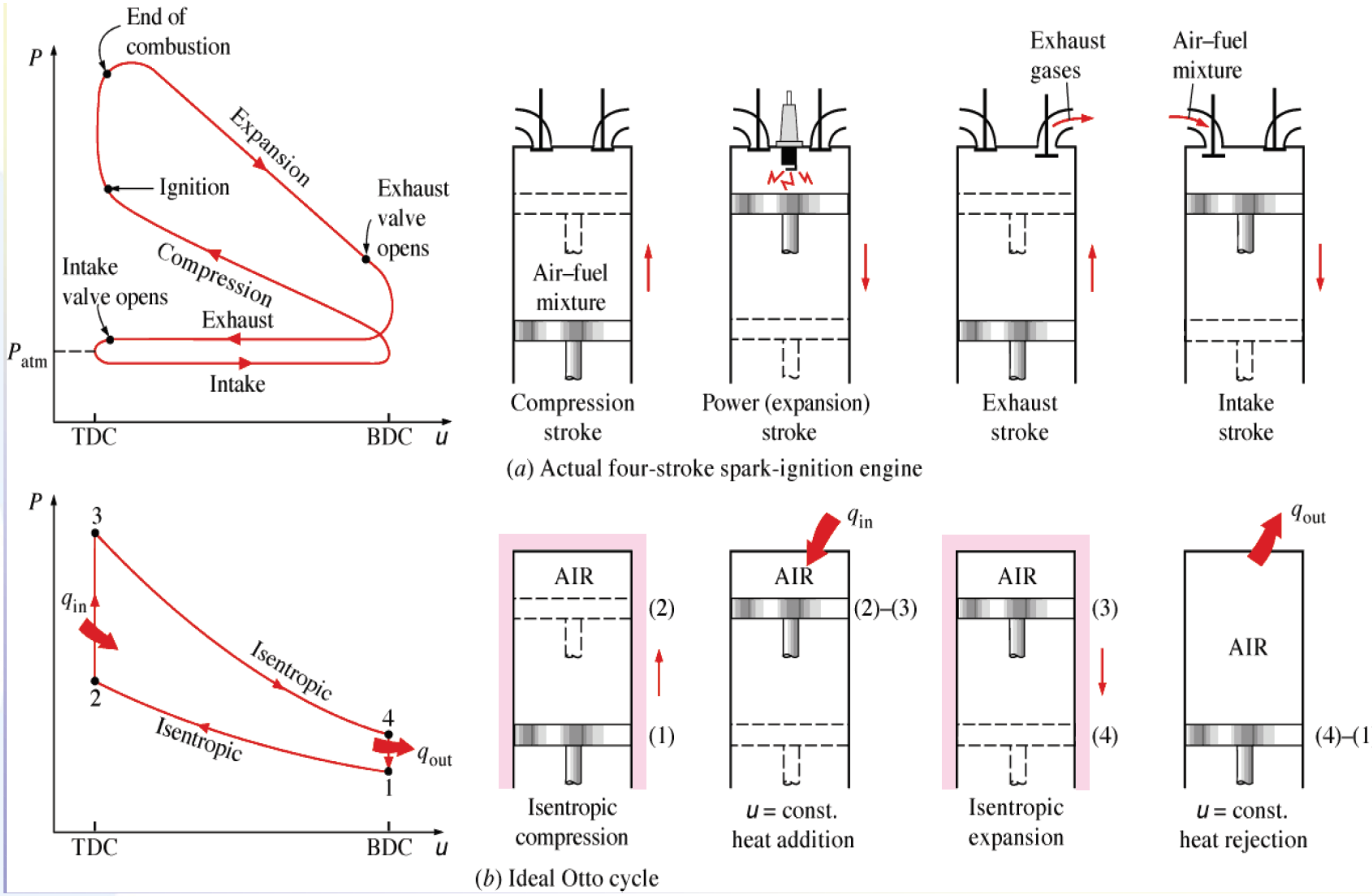
# Actual vs air-standard cycle

- The gas mixture in the cylinder is treated as air for entire cycle and the property of air is used in thermodynamic analyses (a good approximation does not give large error).
- The real open cycle is changed into a closed cycle by assuming that the gases being exhausted are fed back into the intake system (both intake gases and exhaust gases are air).
- The combustion process is replaced with a heat addition term $Q_{in}$ of equal energy value.
- The open exhaust process, which carries a large amount of enthalpy out of the system, is replaced with a closed system heat rejection process $Q_{out}$ of equal energy value.

# Actual vs air-standard cycle

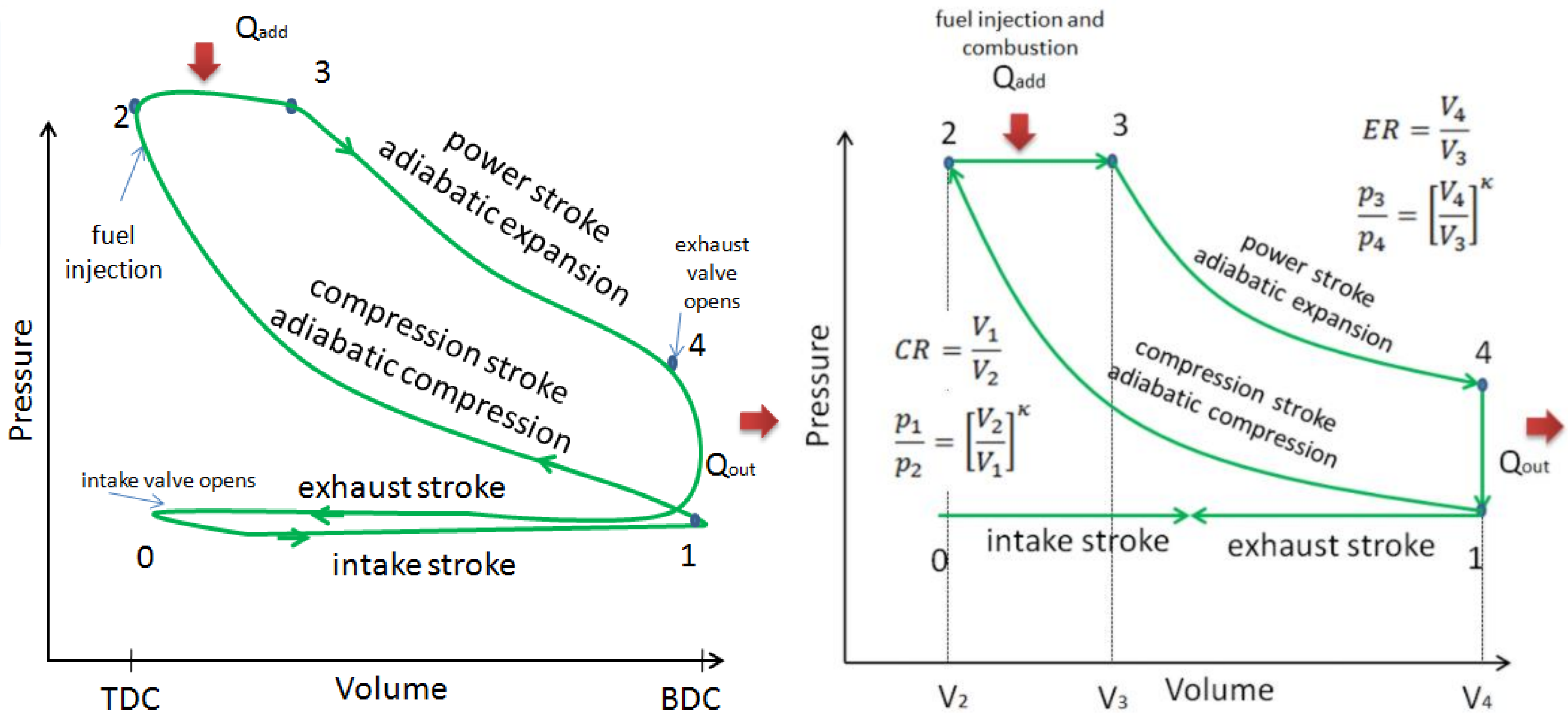
- Compression and expansion strokes are approximated by isentropic processes (reversible and adiabatic).
  i. The friction between the cylinder and piston is minimized (to be assumed frictionless), highly polished and lubricated.
  ii. The heat transfer during these strokes are negligibly small due to the short time involved for a single process.
- Exhaust blow down is approximated by a constant-volume process.
- All processes are considered reversible.
- Air is considered as an ideal gas, and the ideal gas relationships can be used.

# Actual vs air-standard cycle




Actual and ideal cycles in Spark ignition engines

# Actual vs air-standard cycle




Actual and ideal cycles in compression ignition engines

# Otto Cycle

- This cycle is named after Nicholaus August Otto, who invented his first engine in 1876, it forms the basis analysis for spark ignition engines, petrol or gas engine, or high-speed oil engines
- Four non-flow processes are undergone in a cycle.

1. An intake stroke that draw the combustible mixture of fuel and air into the cylinder.
2. A compression stroke with closed valves, which raises the temperature of the mixture, a spark ignite the mixture toward the end of this stroke.
3. An expansion or power stroke, resulting from combustion.
4. An Exhaust stroke which expelled out the product of the burnet gas.

# Otto Cycle

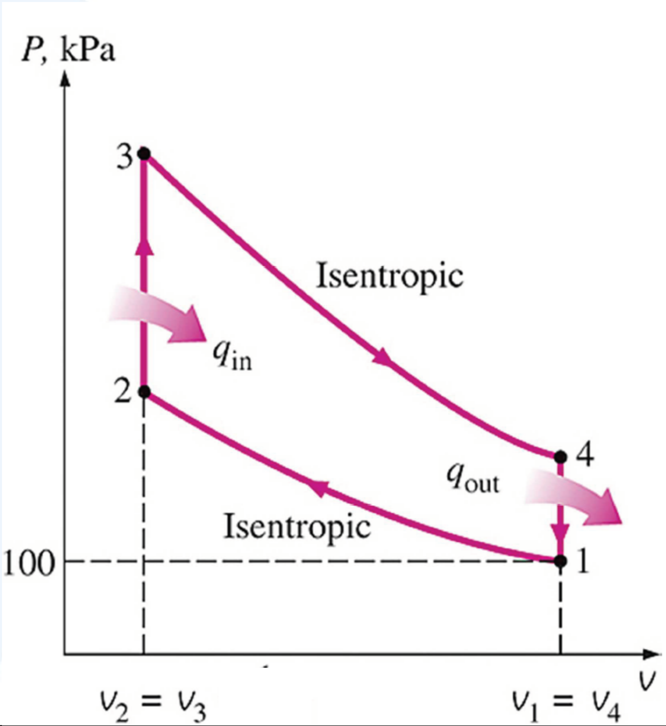
- The Otto cycle is shown on a pressure-volume ($pv$) diagram .

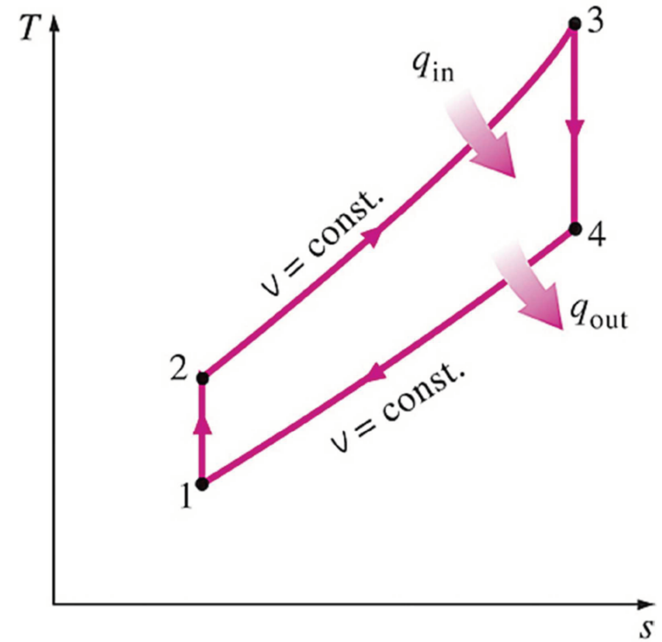
i. 1-2 Isentropic compression.

ii. 2-3 Constant-volume heat addition.

iii. 3-4 Isentropic expansion.

iv. 4-1 Constant-volume heat rejection.



# Otto Cycle

| *Process* | *Description* | *Related formula* |
|---|---|---|
| 1-2 | Isentropic compression | $\frac{P_1}{P_2}=\left(\frac{V_2}{V_1}\right)^k=\left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}}$ |
| 2-3 | Constant volume heat addition | $Q_{in}=mC_v\left(T_3-T_2\right)$ |
| 3-4 | Isentropic expansion | $\frac{P_3}{P_4}=\left(\frac{V_4}{V_3}\right)^k=\left(\frac{T_3}{T_4}\right)^{\frac{k}{k-1}}$ |
| 4-1 | Constant volume heat rejection | $Q_{out}=mC_v\left(T_4-T_1\right)$ |

# Otto Cycle

- In Otto cycle, if the if the specific heats of the air are taken to be constant throughout the cycle, as a first approximation, then:

$$q_{23} = c_v(T_3 - T_2)$$

$$q_{41} = c_v(T_1 - T_4).$$

- Hence, the efficiency of the cycle is $\eta = \frac{q_{23}+q_{41}}{q_{23}} = 1 - \frac{T_4 - T_1}{T_3 - T_2}$.
- For two isentropic processes,

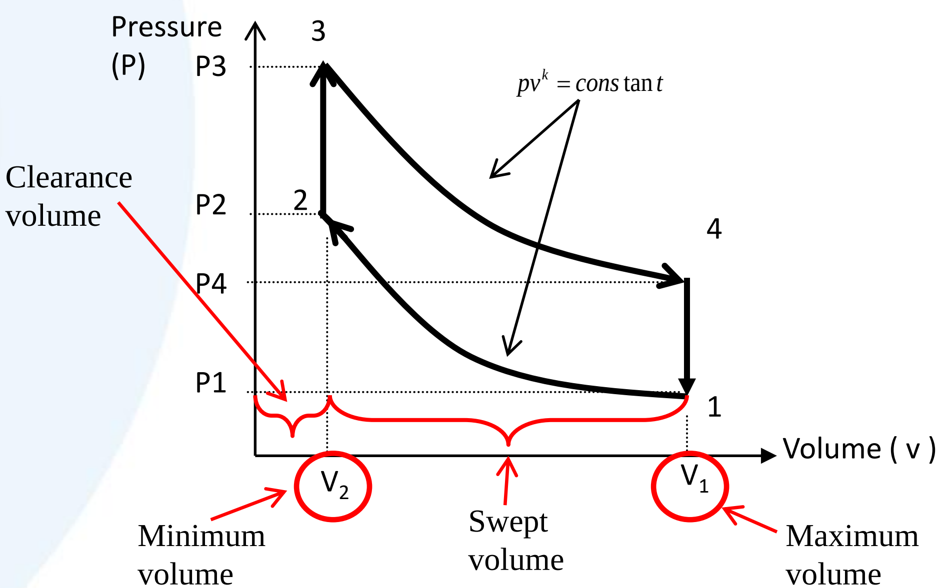
$$\frac{T_2}{T_1} = \frac{T_3}{T_4} = {r_v}^{k-1},$$

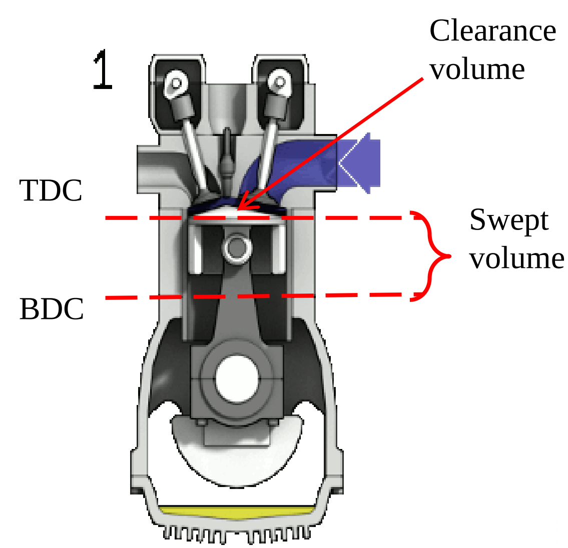
$$\eta = 1 - \frac{T_3 {r_v}^{-(k-1)} - T_2 {r_v}^{-(k-1)}}{T_3 - T_2} = 1 - {r_v}^{-(k-1)}$$

## Compression ratio

To give direct comparison with an actual engine the ratio of specific volume, $r_v = v_1/v_2$, is taken to be the same as the compression ratio of the actual engine.

$$r_v = \frac{v_1}{v_2} = \frac{\text{Swept Volume+Clearence volume}}{\text{Clearence volume}}.$$



## Example 2.1

An Otto cycle in a petrol engine with a cylinder bore of 55 mm, a stroke of 80 mm, and a clearance volume of 23.3 $cm^3$ is given. Find the compression ratio of this engine.

$V_s = 190.7\ \text{cm}^3$, $r_v$ =9.16

# Otto Cycle

**Example 2.2**

A petrol engine is working at a constant volume, the compression ratio is $8.5\colon 1$. Pressure and temperature at a beginning compression process is $101\ \mathrm{kN/m^2}$ and $84°\mathrm{C}$. Temperature at the beginning of an expand process is $1496°\mathrm{C}$. Calculate the temperature and pressure at the each points based on the Otto cycle, and the thermal efficiency.

Take R = $287\ J/kgK$, and $k = 1.4$.

# Otto Cycle

**Example 2.3**

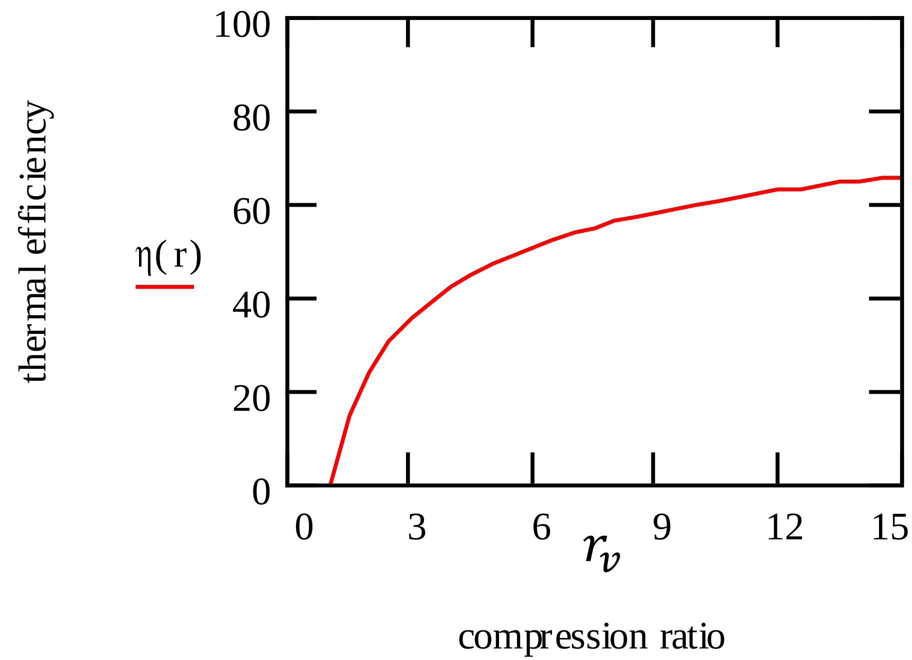
A four cylinder engine operates in Otto cycle, the volume is constant and the compression ratio is $9:1$, beginning pressure is $105\ \mathrm{KN/m^2}$, temperature is $83℃$ and final temperature is $1520℃$. Draw a *p-v* diagram and find the temperature and pressure for each point. Lastly calculate the efficiency of Otto cycle.

Take R = $287\ J/kgK$, and $k = 1.4$.

58.5%

# Otto Cycle

$$\eta(r_v) = 1 - r_v^{-(k-1)}$$



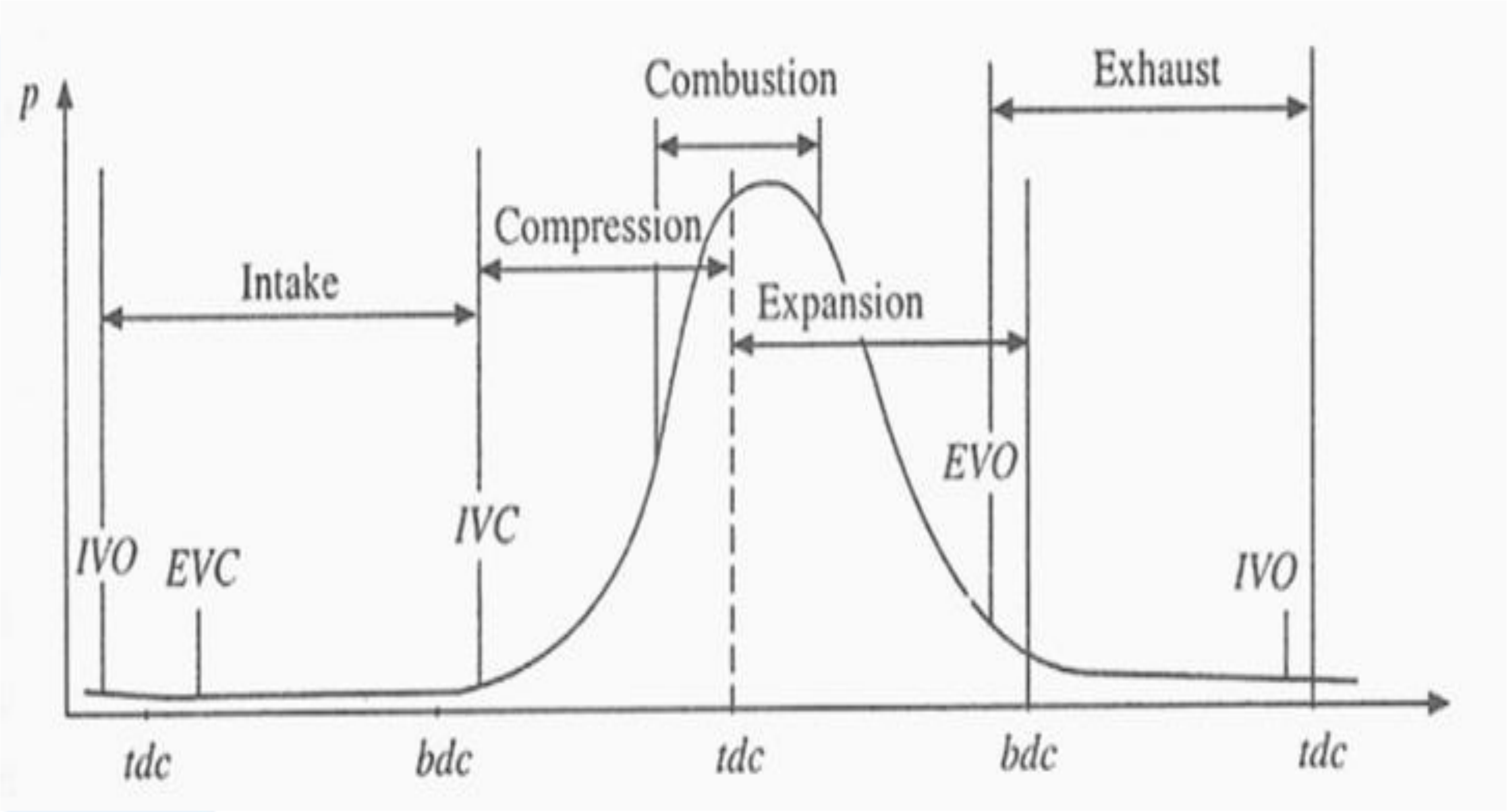

- The higher the compression ratio, the higher the thermal efficiency.
- Higher $r_v$ will led to engine knock (spontaneous ignition) problem.
- Typical value of r for a real engine: between 7 and 10.

# Otto Cycle

## Improvement of Performance

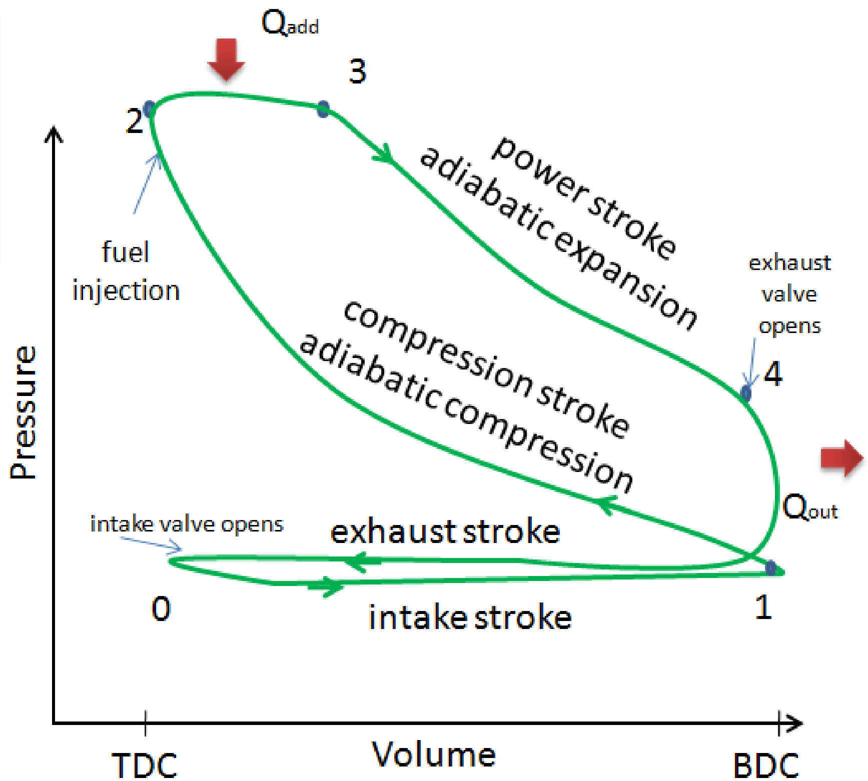
- Increase the compression ratio.
- Increase the engine displacement: more power.
- Compress more air into the cylinder during intake: using supercharger and turbocharger.
- Cool the air before allowing it to enter the cylinder: cooler air can expand more, thus, increase the work output.
- Reduce resistance during intake and exhaust stages: multiple valve configuration: 4 cylinders/16 valves engine.
- Fuel injection: do away with the carburetor and provide precise metering of fuel into the cylinders.

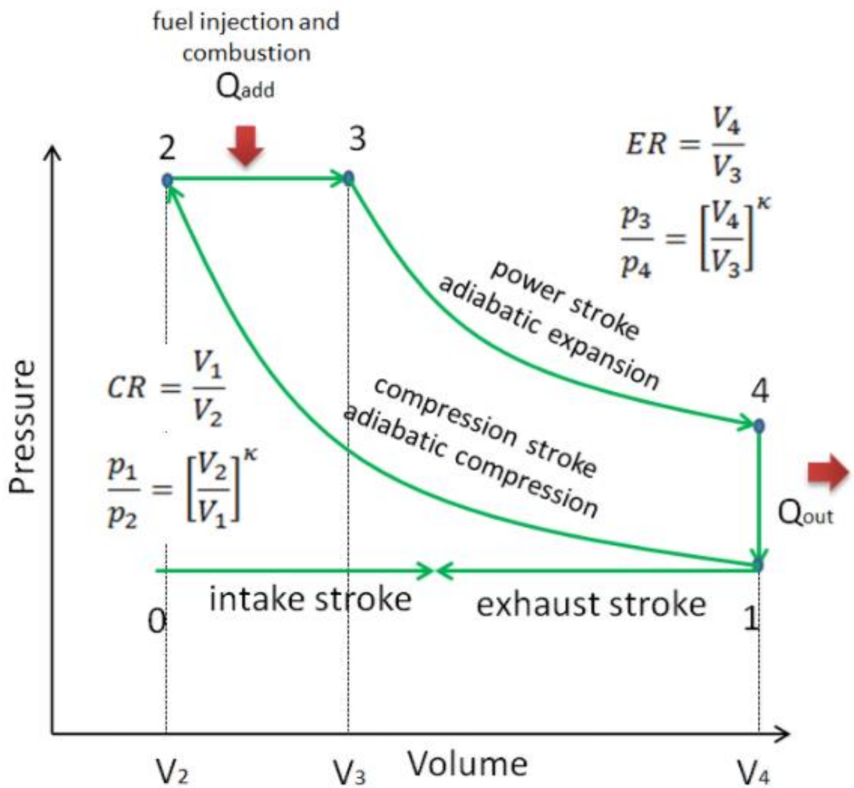
# Otto Cycle



p
Combustion
Exhaust
Compression
Intake
Expansion
EVO
IVC
IVO
EVC
IVO
tdc
bdc
tdc
bdc
tdc

# Diesel Engines



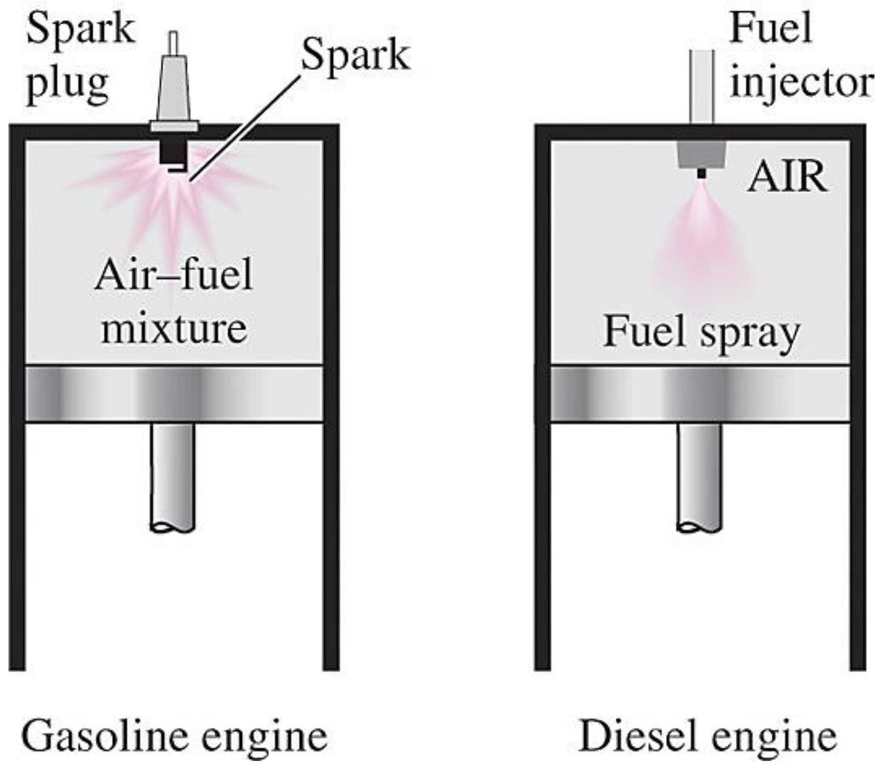

Actual and ideal cycles in compression ignition engines

# Diesel Engines

- This cycle is named after the German engineer **Rudolf Diesel** to outlined in his patent a new form of internal combustion engine in 1892.
- His concept of initiating combustion by injecting a liquid fuel into air heated solely by compression permitted a doubling of efficiency over other internal combustion engines.
- The basic construction of the diesel engine is same as that of the Otto petrol engine, except instead of spark plug, a fuel injector is mounted in its place .
- In this cycle, heat is added at constant pressure and rejected at constant volume.

# Diesel Engines

There are no spark plugs in a diesel engine. The fuel is injected at the time of maximum compression (near TDC) and the heat of compression causes combustion.



# Diesel Cycle

- Four non-flow processes are undergone in a cycle.
  1. An intake stroke that draw the air only into the cylinder.
  2. A compression stroke with closed valves, which raises the temperature of the air.
  3. An expansion or power stroke, resulting from injecting the fuel into the compressed hot air (causing the combustion).
  4. An Exhaust stroke which expelled out the product of the burnet gas.
- Fuel injection for an extended period during the power stroke and therefore maintaining a relatively constant pressure.

# Diesel Cycle

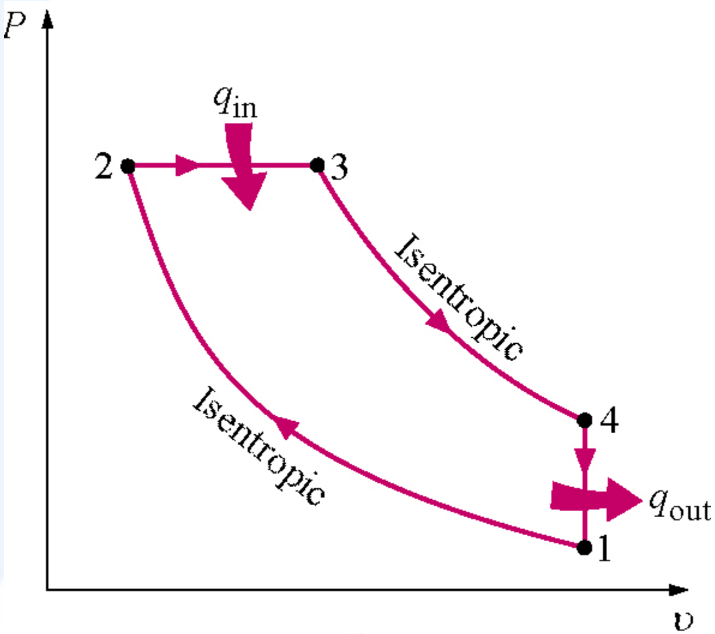
- The Diesel cycle is shown on a pressure-volume ($p - v$) diagram .

i. 1-2 Isentropic compression.

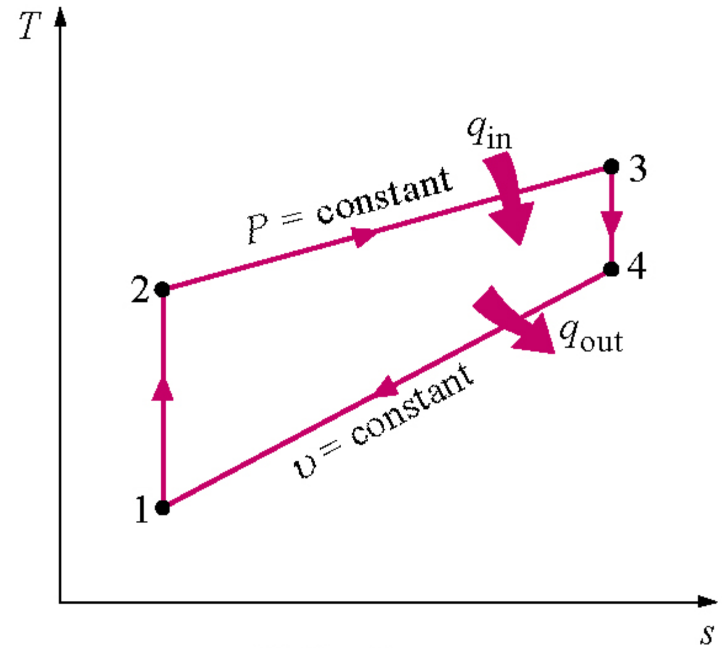
ii. 2-3 Constant-pressure heat addition.

iii. 3-4 Isentropic expansion.

iv. 4-1 Constant-volume heat rejection.




(a) P-υ diagram




(b) T-s diagram

# Diesel Cycle

| *Process* | *Description* | *Related formula* |
|---|---|---|
| 1-2 | Isentropic compression | $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^k = \left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}}$ |
| 2-3 | Constant pressure heat addition | $Q_{in} = mC_P\left(T_3 - T_2\right)$ |
| 3-4 | Isentropic expansion | $\frac{P_3}{P_4} = \left(\frac{V_4}{V_3}\right)^k = \left(\frac{T_3}{T_4}\right)^{\frac{k}{k-1}}$ |
| 4-1 | Constant volume heat rejection | $Q_{out} = mC_v\left(T_4 - T_1\right)$ |

$$r_v = \frac{v_1}{v_2} = Compression\ ratio, \quad and \quad r_c = \frac{v_3}{v_2} = Cut-off\ \ ratio.$$

# Diesel Cycle

- In the Diesel cycle, if the if the specific heats of the air are taken to be constant throughout the cycle, as a first approximation, then:

$$q_{23} = c_p(T_3 - T_2)$$

$$q_{41} = c_v(T_1 - T_4).$$

- Hence, the efficiency of the cycle is $\eta = \frac{q_{23}+q_{41}}{q_{23}} = 1 - \frac{c_v(T_4-T_1)}{c_p(T_3-T_2)}.$

$$\frac{T_4}{T_1} = \frac{p_4}{p_1}, \qquad \frac{T_3}{T_2} = \frac{v_3}{v_2} = r_c$$

$$\frac{p_4}{p_1} = \left(\frac{v_3}{v_2}\right)^k = r_c{}^k,$$

$$\boxed{\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}} \frac{r_c{}^k - 1}{k\left(r_c - 1\right)}}$$

# Diesel Cycle

**Example 2.4**

Diesel engine has an inlet temperature and a pressure at 15°C and 1 bar respectively. The compression ratio is $12:1$ and the maximum cycle temperature is 1100°C. Calculate the temperature and pressure at each points, the cut-off ratio and the thermal efficiency based on the diesel cycle. Take $c_v = 0.718\ k\mathrm{J/kg.K}$, and $c_p = 1.005\ k\mathrm{J/kg.K}$

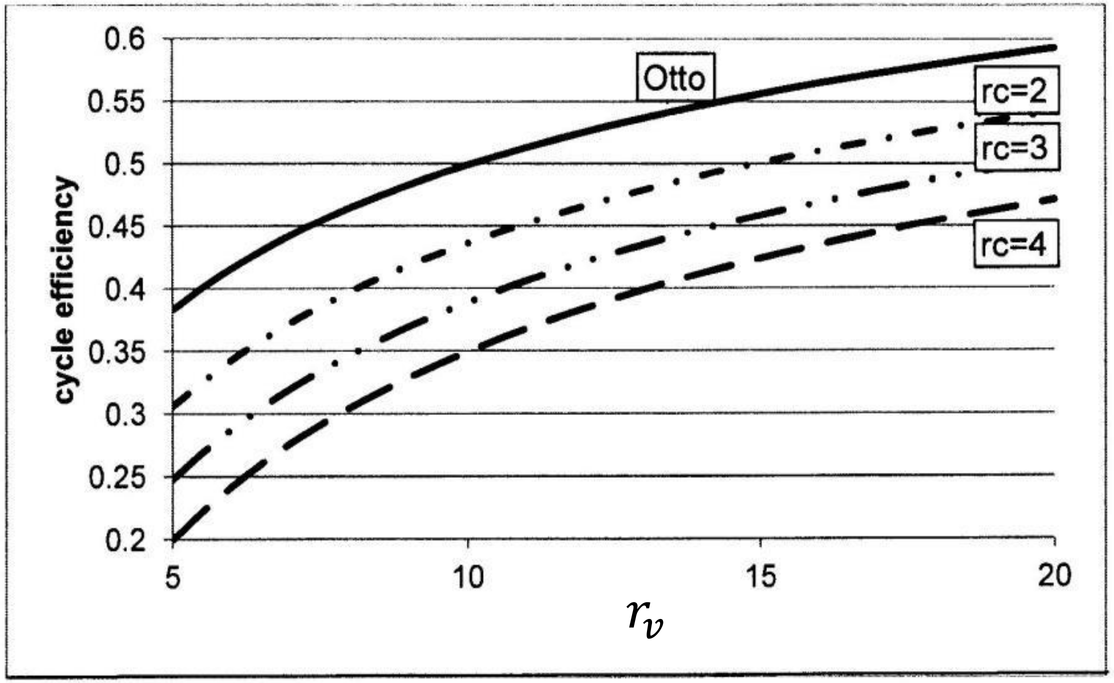
$p_4 = 2.21$ bar, $T_4 = 637.67$ K, $r_c = 1.764$, 58%

## Example 2.5

An engine was operated with diesel cycle process with the beginning temperature and pressure at 16.8℃ and 1.05 bar. The compression ratio for this engine is 12.5 and cut of ratio for this engine is 1.75. Calculate the heat added to the engine through combustion, the heat lost with the exhaust, thermal efficiency for this engine. Take $c_v = 0.718\ k$J/kg.K, and $c_p = 1.005\ k$J/kg.K

$q_{in} = 599.91\ k$J/kg, $q_{out} = 247.4\ k$J/kg , 58.8%

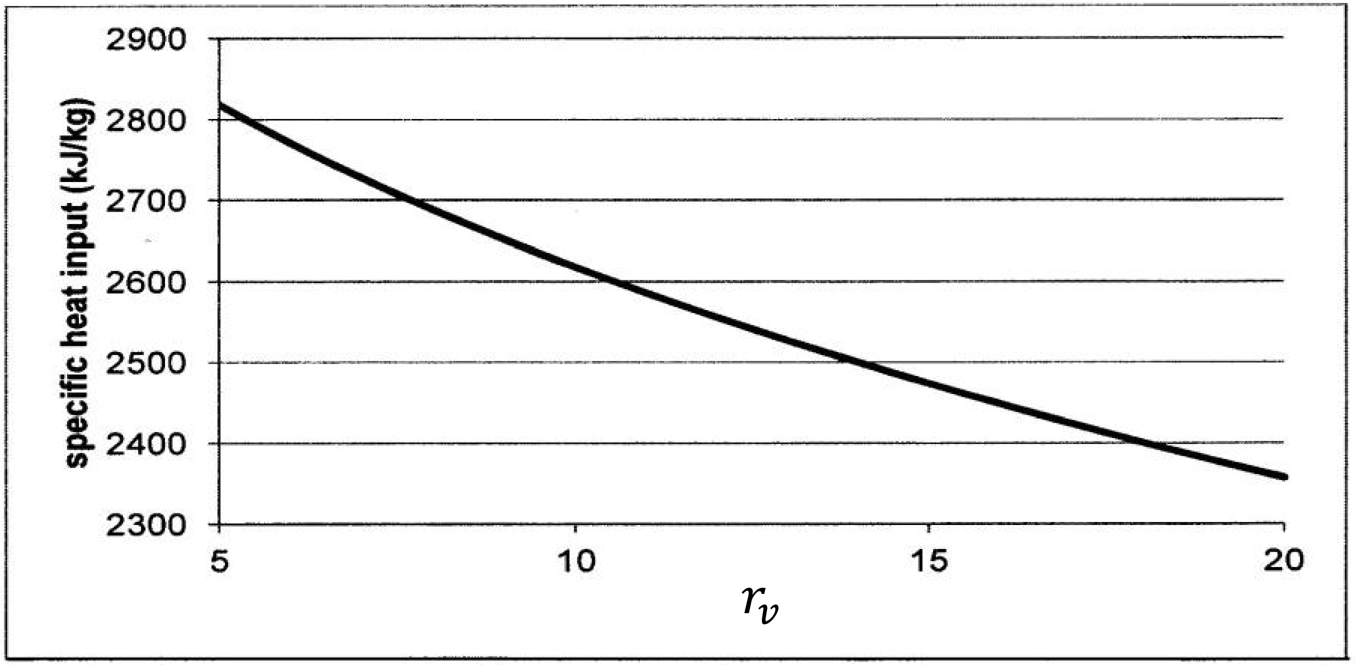
# Diesel Cycle




$$\eta_{th,Diesel} = 1 - \frac{1}{r^{k-1}} \frac{r_c^{\,k} - 1}{k(r_c - 1)}$$

- Since $v_3$ cannot be greater than $v_1$, $r_c$ must be less than or equal to $r_v$.
- Clearly η decreases with increasing $r_c$. This is because heat is being input into a larger volume, with a lower mean temperature, if $r_c$ is increased, the heat is therefore unable to produce as much work

# Diesel Cycle




- The $r_c$ can be considered as a measure of the air/fuel mass ratio in the Diesel cycle, with low values of $r_c$ indicating very lean combustion conditions.
- As the compression ratio becomes lower the heat input requirements are larger because $T_2$ is smaller.

# Diesel Cycle

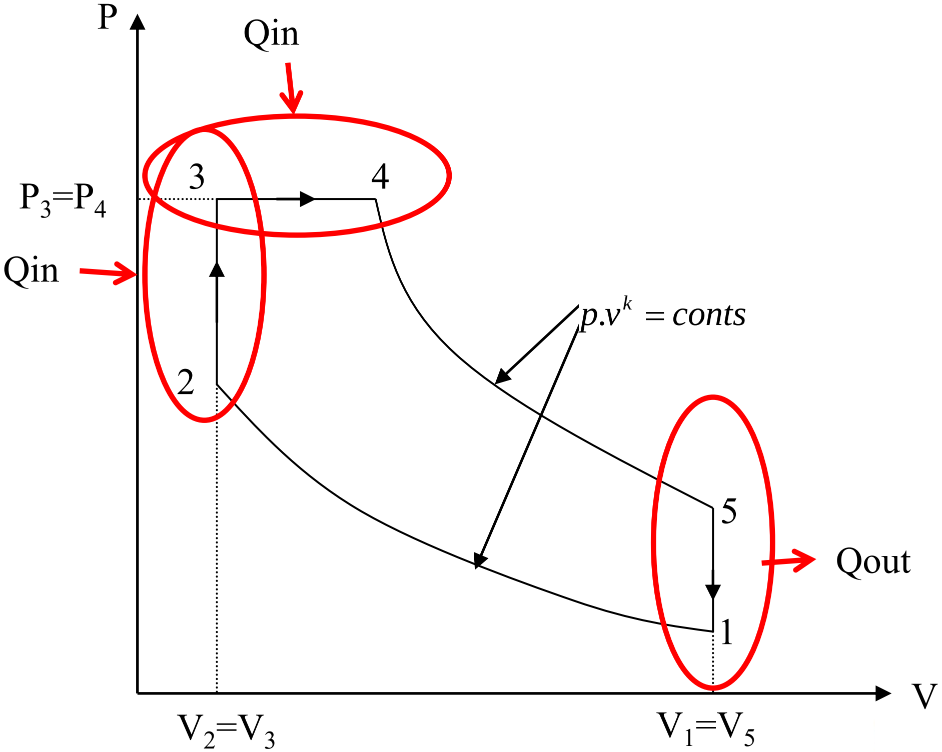
- In operating Diesel engines the peak pressures may be up to 120 bar.
- This could not be achieved by an engine operating on the Diesel cycle because this would require compression ratios of more than 30.
- The operating Diesel engines have a dual mode of heat release due to combustion.
- The first component, due to the combustion of pre-mixed fuel and air prior to ignition, results in essentially constant volume combustion.
- The second component depends on further fuel/air mixing and later combustion and this component is close to constant pressure combustion.
- Thus a real Diesel engine actually operates on a variant of the dual cycle

# Dual Cycle

- Both the Otto and Diesel cycles are idealised and cannot be achieved in practice.
- Constant volume combustion implies an infinite rate of combustion or that the volume change is very small because of low engine speed.
- In reality the combustion rate roughly scales with engine speed.
- Constant pressure combustion implies that the rate of combustion increases during the combustion process to compensate for the increasing rate of change of cylinder volume.
- This cannot be completely achieved because as combustion progresses oxygen is consumed and hence the reaction rate tends to decrease well before the fuel is fully burned.

# Dual Cycle

- A more realistic air-standard cycle is the dual cycle.
- The heat addition due to combustion is divided into two parts; constant volume process with pressure ratio, and constant pressure process with cut-off ratio.



# Dual Cycle

## Dual/Combined Cycle Process:

- 1 to 2 is isentropic compression with compression ratio $r_v = v_1/v_2$ .
- 2 to 3 is reversible constant volume heating, the heat supplied $Q_{in1}$, and pressure ratio $r_p = p_3/p_2$.
- 3 to 4 is reversible constant pressure heating, the heat supplied $Q_{in2}$ , $r_c = v_4/v_3$, cut off ratio.
- 4 to 5 is isentropic expansion.
- 5 to 1 is reversible constant volume cooling, the heat rejected $Q_{out}$.

# Dual Cycle

| *Process* | *Description* | *Related formula* |
|---|---|---|
| 1-2 | Isentropic compression | $\frac{P_1}{P_2} = \left(\frac{V_2}{V_1}\right)^k = \left(\frac{T_1}{T_2}\right)^{\frac{k}{k-1}}$ |
| 2-3 | Constant volume heat addition | $Q_{in1} = mC_v(T_3 - T_2)$ |
| 3-4 | Constant pressure heat addition | $Q_{in2} = mC_p(T_4 - T_3)$ |
| 4-5 | Isentropic expansion | $\frac{P_4}{P_5} = \left(\frac{V_5}{V_4}\right)^k = \left(\frac{T_4}{T_5}\right)^{\frac{k}{k-1}}$ |
| 5-1 | Constant volume heat rejection | $Q_{out} = mC_v(T_5 - T_1)$ |

$$p_r = \frac{v_1}{v_2},\ p_r = \frac{p_3}{p_2} \quad and \quad r_c = \frac{v_3}{v_2}.$$

# Dual Cycle

The same procedures can be applied to Dual cycle (as in Otto and Diesel cycles). Upon substitutions, the thermal efficiency of Dual cycle becomes

$$\eta_{th} = 1 - \frac{r_p r_c^k - 1}{\left[\left(r_p - 1\right) + k c_p \left(r_c - 1\right)\right] r_v^{k-1}}$$

# Dual Cycle

**Comparison of Otto, Diesel and Dual cycle**

- For same compression ratio and same heat input:

$$\eta_{Otto} > \eta_{Dual} > \eta_{Diesel} \cdot$$

- For constant maximum pressure and same heat input:

$$\eta_{Diesel} > \eta_{Dual} > \eta_{Otto} \cdot$$

- For same maximum pressure and temperature:

$$\eta_{Diesel} > \eta_{Dual} > \eta_{Otto} \cdot$$

- For same maximum pressure and output:

$$\eta_{Diesel} > \eta_{Otto} \cdot$$

# Dual Cycle

**Example 2.6**

An oil engine takes in air at 1.01 bar, 200 °C and the maximum cycle pressure is 69 bar. The compression ratio is 18/1. Draw the $p-v$ diagram, calculate the net work per cycle and the air standard thermal efficiency based on the dual combustion cycle. Assume that the heat added at constant volume is equal to the heat added at constant pressure. Take $c_v = 0.718\ k\text{J/kg.K}$, and $c_p = 1.005\ k\text{J/kg.K}$

$w_{net} = 177.17\ k\text{J/kg}$, 68.2%

# Atkinson cycle

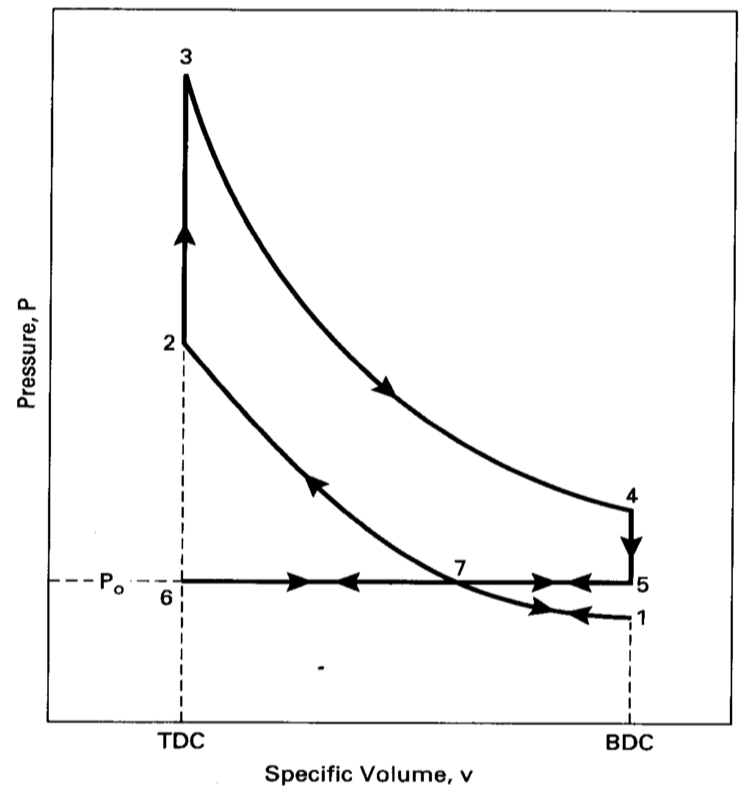
- In the classic Otto and Diesel cycles, when the valve is open near to the end of the expansion stroke pressure in the cylinder is still 3-5 times of the atmospheric pressure.
- A potential for doing additional work during the stroke power is lost when the valve is opened to reduce the pressure to atmospheric.
- If the valve is not allowed to be open until the pressure inside the cylinder is atmospheric, then a greater work would be obtained in the expansion stroke.
- The greater work means a higher thermal efficiency.
- Such air cycle is so called  an Atkinson cycle or overexpended cycle.

# Miller cycle

- In the real world a number of crank and valves mechanisms were tired to achieve this cycle, which has a longer expansion stroke than compression, but no large number of these engines were been marked indicating the failure of this development.
- A new cycle was developed by Miller, Miller cycle, which is modification of the Atkinson cycle has an expansion ratio greater than the compression ratio.
- In Miller cycle, engine uses unique valve timing to obtain the same desired results instead of the mechanical linkage system of some kind.
- The amount of air ingested into each cylinder is then controlled by closing the intake valve at the proper time long before BDC.

# Miller cycle

- As the piston then continues towards BDC during the latter part of the intake stroke, cylinder pressure is reduced along process 7-1.
- When the piston reaches BDC and starts back towards TDC cylinder pressure is again increased during process 1-7.
- The resulting cycle is 6-7-1-7-2-3-4-5-6. The work produced in the first part of the intake process 6-7 is cancelled by part of the exhaust stroke 7-6, process 7-1 is cancelled by process 1-7, and the net indicated work is the area within loop 7-2-3-4-5-7.



# Miller cycle

- The shorter compression stroke which absorbs work, combined with the longer expansion stroke which produces work, results in a greater net indicated work per cycle.
- When the piston reaches BDC and starts back towards TDC cylinder pressure is again increased during process 1-7.
- Miller cycle engine has essentially no pump work (ideally none), much like a CI engine. This results in higher thermal efficiency.
- The mechanical efficiency of a Miller cycle engine would be about the same as that of an Otto cycle engine, which has a similar mechanical linkage system. An Atkinson cycle engine, on the other hand, requires a much more complicated mechanical linkage system, resulting in lower mechanical efficiency.

# Miller cycle

- It is extremely important to be able to close the intake valve at the precise correct moment in the cycle (point 7).
- At this point where the intake valve must close changes as the engine speed and/or load is changed. This control was not possible until variable valve timing was perfected and introduced.
- Vehicles with Miller cycle engines were first marketed in the latter half of the 1990s. A typical value of the compression ratio is about 8:1, with an expansion ratio of about 10:1.
- A number of car are based on Miller cycles such as Mazda Millennia, A4 (2016).